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Columbus' footprint in Hispaniola: A paleoenvironmental record of indigenous and colonial impacts on the landscape of the central Cibao Valley, northern Dominican Republic

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ABSTRACT

The 1100-year sedimentary record of Laguna Biajaca reveals human-driven landscape changes in the central Cibao Valley, Dominican Republic, Hispaniola. This sediment-filled cutoff meander is located in close proximity to pre-Colonial archaeological sites and a Colonial urban hub. It provided a nutrient-rich floodable locus for agricultural activities for indigenous communities and for the first introduction of Old World crops and cattle in the Americas. Integration of paleoecological proxies revealed the formation of a clear-water body surrounded by a palm-rich forested landscape around 1100 cal yr BP. Changes in the drainage system were linked to human-driven deforestation, which also changed the composition of the vegetation and fungal communities around the site between AD 1150 and 1500 (800 and 700 cal yr BP). Pre-Colonial modifications of the landscape were primarily the result of fire-use and small-scale clearings. Crop cultivation developed between AD 1250 and 1450 (700–500 cal yr BP). Within decades after Columbus' arrival in Hispaniola in AD 1492, the first impacts of European colonization included the abandonment of indigenous sites and the introduction of Old World domesticated animals. During the 15th and 16th centuries the area underwent intensive land-clearing that allowed for larger scale crop cultivation. An increase of aquatic vegetation points to sediment-filling around AD 1700 (250 cal yr BP). At that time, cattle breeding expanded and rapidly provoked eutrophication while, concurrently, monocultures became regionally established. This paper provides a framework of past environmental dynamics and offers an opportunity to place archaeological findings in a context of natural and anthropogenic change.

1. Introduction

Multi-proxy paleoenvironmental studies of records spanning the last millennia have the potential to shed light on the complex relationships between social and environmental phenomena (Kirch, 2009; Dearing et al., 2015). To date, our understanding of long-term culture-environment interactions in the interior valleys of Hispaniola is based on the distribution of archaeological sites and the study of written sources (Armstrong et al., 2009; Delle, 2014; Ulloa Hung, 2014). Only a few studies in the Caribbean archipelago have successfully linked archaeo-historical evidence and research questions related to environmental change (*e.g.* Siegel et al., 2005; Beets et al., 2006; Rivera-Collazo et al., 2015; Siegel et al., 2015). For instance, mid-to-late Holocene paleoclimatological studies, some including fire-history reconstructions, have identified human and climatic-driven landscape changes in Hispaniola: Lake Miragoane (Higuera-Gundy et al., 1999) and

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Laguna Saladilla (Caffrey et al., 2015) in Haiti, and studies in the Dominican Republic's Cordillera Central (Horn et al., 2000; Horn et al., 2001; Clark et al., 2002; Kennedy et al., 2005, 2006, Lane et al., 2008, 2009) and coastal areas (Desjardins, 2007; LeBlanc, 2011; McVay, 2013).

Paleoecological landscape reconstructions can help identify the impacts of human activities and the timing and effects of the introduction of exogenous biota on insular settings. The Cibao Valley, northern Dominican Republic, is an excellent location to better understand pre-Colonial landscape modification and the process through which the first colonial landscapes emerged in the Americas. Moreover, the present-day landscapes of the northwestern Dominican Republic are considered ecologically vulnerable (UNEP, 2013), and paleoecological studies of the Cibao Valley could be essential to help develop new strategies to manage and prevent further decline.

This paper presents a multi-proxy paleoecological study of the last 1100 years from Laguna Biajaca sediments, a former meander cutoff of the Yaque River located in the area of the city of Mao, northwestern Dominican Republic. We aim to reconstruct human-induced landscape modification since the start of the Late Ceramic Age (ca. AD 950) and to document the landscape transitions during the Early Colonial Period (AD 1492–1600) and human impacts on the landscape during the Late Colonial Period until the present day (AD 1600-present). The objective of this study is to provide high resolution records of fire-history, agriculture, grazing and fluvial dynamics in order to explore the scale and intensity of environmental change, and to determine the main culture-environmental drivers and feedbacks of the system.

2. Setting

2.1. Archaeological and ethno-historical context

Before European contact, indigenous communities altered the ecosystems of the insular Caribbean, often through exchange and migration (Steadman et al., 2005; Fitzpatrick and Keegan, 2007). Archaeological evidence suggests Hispaniola was first occupied around 5500 years ago by foraging groups labeled as Casimiroid peoples who settled mostly in coastal areas (Veloz Maggiolo, 1980; Wilson, 1990; Rouse, 1992). The first arrival of full pottery-making horticulturalists originating from Puerto Rico is thought to have occurred ca. AD 950. These people probably first settled in the coastal areas and were archaeologically related to the Ostionoid ceramic tradition. Caribbean indigenous societies were diverse and highly mobile, and during the Late Ceramic Age (AD 1000–1492), archaeological evidence indicates the existence of dynamic inter-island networks through which animals, plants goods and ideas were translocated and exchanged (Rodríguez Ramos and Pagán-Jiménez, 2006; Hofman et al., 2007, 2014; Hofman and Hoogland, 2011). The Cibao Valley and the northern coast of the Dominican Republic concentrate evidence of intensive occupation in this period, as archaeologists have documented numerous archaeological sites (*e.g.* Ulloa Hung and Herrera Malatesta, 2015; Hofman and Hoogland, 2015; Sonnemann et al., 2016; Hofman et al., 2018) (Fig. 1). Radiocarbon dating suggests that some of these sites were occupied during and after European contact (Ulloa Hung, 2014).

Most of our knowledge about Taíno society derives from Columbus' diaries and posterior ethno-historical sources (de Oviedo y Valdés, 1851; de Las Casas, 1875; Arrom, 2001; Arranz,

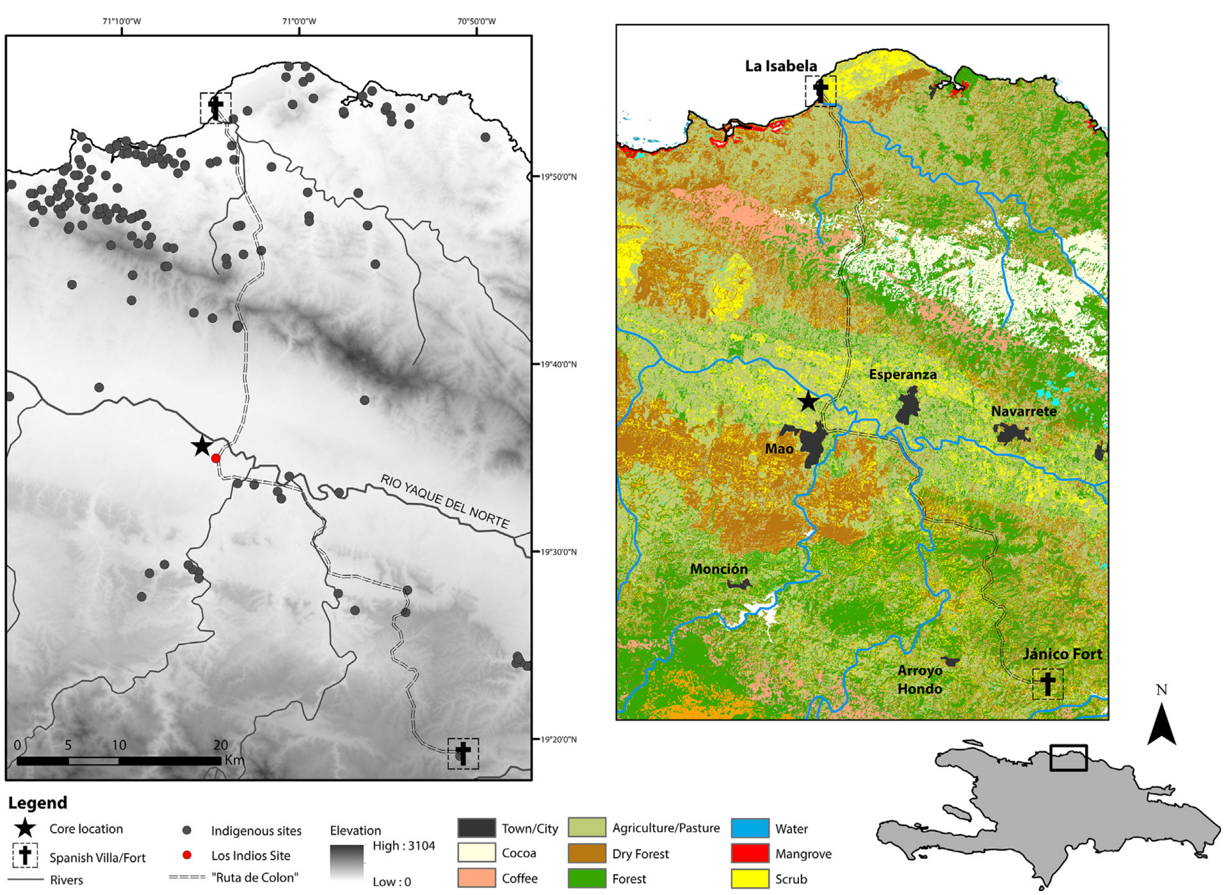

Fig. 1. Left panel: map of the central Cibao Valley with the location of Laguna Biajaca, archaeological indigenous sites, Spanish early settlements and the Ruta de Colón. Right panel: present-day vegetation and urban hubs. DEM based on an Aster GDEM image: https://gdex.cr.usgs.gov/gdex/. ASTER GDEM is a product of NASA and METI. Vegetation map from ASTER GDEM is a product of NASA and METI. Vegetation map from Atlas de Biodiversidad y Recursos Naturales de la República Dominicana.

2006). For instance, Columbus and his companions described a densely populated valley where indigenous communities practiced agriculture of manioc, sweet potato and maize, as well as a variety of herbs, such as tobacco (Fernández de Oviedo, 1851; de Las Casas, 1875). Cultivation took place in gardens or *conucos*, also using raised mounds (*montones*) and irrigation techniques (Cassá, 1989; Keegan, 2013, p. 72; Keegan and Hofman, 2017). The consumption of these staple crops, as well as chili pepper and guáyiga (*Zamia* spp.), has been documented by starch grain analyses in human dental material and artifacts from southeastern Hispaniola (Mickleburgh and Pagán-Jiménez, 2012). However, little is known about the relation of these economic practices to small and big-scale fire events, and their impact on the Cibao Valley's environment.

After the Spanish conquest, the landscapes of the Caribbean were re-shaped and organized around the extraction of precious metals and the large-scale production of crops and commodities for overseas markets (Tanodi, 1971; Crosby, 1972, 2004 ; McCook, 2011). Economic plants and animals were transported by the new settlers in order to change and manage the island's environment, transforming it into more familiar, European-like landscapes (Kirch, 1982; Watts, 1987; Ejarque et al., 2015). The Early Colonial period in Hispaniola was marked by the imposition of the Castilian *encomienda* socio-political system upon the native populations, and the increasing influx of enslaved indigenous populations from the circum-Caribbean and enslaved Africans (Deive, 2002; Valcárcel Rojas, 2012; Anderson-Córdova, 2017). The implementation of *encomienda* unleashed processes of transculturation and domination (Deagan and Cruxent, 2002; Crosby, 2004) and drastic changes in demography (Dobyns, 1983). Nevertheless, the extent and pace of the impact on the island's ecology, the decrease of native populations due to the devastation caused by Old World diseases, as well as the new European economic activities, have not yet been closely examined at different times and scales (Watts, 1999, p. 37).

The 16th and 17th centuries were marked by Spanish institutional, and private, investment in the extraction and production of coveted resources. Gold and silver were the primary targets. This motivated Spaniards to open routes towards the island's interior (Pons, 1971; Sued Badillo, 1995). The production of agricultural goods such as sugar (*Saccharum officinarum*; potentially in the pollen record of Poaceae), ginger (*Zingiber officinale*; Zingiberaceae) and tobacco (*Nicotiana tabacum*; potentially in the pollen record of Solanaceae) rapidly followed these efforts, along with the quick expansion of animal husbandry (Artigas et al., 2012; Del Río Moreno, 2012). The 17th century was a period of re-organization of the agricultural economy of the region, linked to the arrival of new animals, technologies and agricultural techniques brought to strengthen the agricultural export economy (Del Río Moreno, 2012). Throughout the late 17th and 18th centuries, Hispaniola saw the emergence of systems of crop monocultures and a plantation economy for commercial crops that has continued to grow to the present day. Combined, these have led to the environmental vulnerability of many areas of the island (UNEP, 2013; Artigas et al., 2012; Altieri and Nicholls, 2001). These economic activities have drastically reduced other agricultural strategies, such as mixed cropping and agroforestry (potentially *Pinus, Alnus, Salix* etc.), impacting biodiversity and local ways of life.

2.2. Study site

Laguna Biajaca is an abandoned meander of the Yaque River of some 400 m length that became filled with sediments after water currents lost most of their energy. The meander is located at 78 m above mean sea level (amsl) to the west of the city of Mao, at 19°35'36.4''N, 71°05'12.5''W (Fig. 1). Currently, the meander is a marshy area and used as a grazing area for cattle. It is surrounded by extensive banana (*Musa acuminata*; Musaceae) and rice (*Oryza sativa*; Poaceae) plantations.

Laguna Biajaca lies at the heart of the Cibao Valley, approximately 1 km from the current course of the Yaque River close to a cluster of pre-Colonial archaeological sites. At ca. 1 km distance is a major north-to-south route through Hispaniola, the so-called 'Ruta de Colón' (Fig. 2). This route was most likely a pre-existing indigenous communication route connecting the coast with the interior of the Cibao Valley (Guerrero and Veloz Maggiolo, 1988; Hofman et al., 2018). Many sites in the interior of the valley have been destroyed through agricultural practices, explaining the scarcity of archaeological sites compared to the hills and mountainous areas surrounding the valley, or the coastal region in the vicinity of La Isabela, the first town established by the Spanish in the Americas (Fig. 1). The archaeological site of 'Los Indios' is situated less than a kilometer from Laguna Biajaca, extending over 4 ha (Hoogland and Ulloa Hung, pers. comm. 2017). Pottery of the Chicoid series has been found on the surface of this site, and one radiocarbon date on a shell produced a date in the late 15th century.

Climatically, the valley follows the general trends in the archipelago: a strong seasonality marked by a wet season (May–November), and a severe dry season (December–April). Tropical storms and hurricanes occur from June to October, during which floods and re-organizations of river drainage systems are common.

3. Materials and methods

This paleoenvironmental reconstruction relies on records from sediments in a meander cutoff. The dynamic drainage system and general levels of erosion in the study area are reflected in the grain size record, while the up-fill of the river bed with organic rich sediments (making the sediment archive) is shown by pollen of aquatic and wetland taxa, plant macrofossils and total organic matter (Toonen et al., 2012). Composition of the regional and local vegetation is shown by the pollen, plant macro-fossil and phytolith records, burning by the charcoal record, and deforestation by the combination of charcoal, pollen and grain size records. Increased use of cattle grazing is indicated by spores of coprophilous fungi, and local agriculture and development of crops by phytoliths and pollen.

3.1. Coring and sampling

A sediment column composed by two parallel 245 cm long half-cylindrical cores lifted at maximally 20 cm distance were collected with a Russian corer of 5 cm diameter and 50 cm length. The half-cylindrical cores were labelled (BC1, BC2) and photographed before wrapping them in plastic foil, protected by half pvc-tubes (Fig. S1). After transport to Amsterdam, sediment cores were stored in a dark and cold (4 °C) room. Our strategy in sampling the two parallel and identical core halves was to provide records of a suite of paleoecological proxies that provide complementary parts of the integrated reconstruction.

3.2. Age-depth model

To develop an age model of the cores we obtained five bulk sediment Accelerator Mass Spectrometry (AMS) radiocarbon ages from Beta Analytics laboratory, Florida, USA (obtained from BC2). An age vs. depth model was obtained by using the Bacon R-Code based on the INTCAL 13 Calibration curve. The *Bacon* model reconstructed the sediment accumulation process in Laguna Biajaca by using Bayesian statistics (Blaauw and Christen, 2011).

Fig. 2. A satellite view of the study area produced with Google Maps (right panel). Photograph of Laguna Biajaca and core section (left panels).

3.3. Grain size distributions

To measure grain size distributions (GSDs) we used a set of 48 1 cm^3 samples taken at 5 cm increments along core BC2. The samples were processed according to Konert and Vandenberghe (1997). Organic matter and carbonates were removed by treating the sediment with HCl and H_2O_2 solutions. Samples were analyzed with a Helium-Neon Laser Optical system (Helos KR)-Laser Particle Sizer, Sympatec Inc. at Vrije Universiteit Amsterdam. Results were reported as different sediment categories depending on grain size. We chose to represent the results per sample as the median grain size value, and the percentages of clay, silt, coarse silt and sand (Prins and Weltje, 1999).

3.4. Total organic content

To measure total organic content (TOC) of the sediments we used the method of loss on ignition (LOI) following Dean (1974) and Heiri et al. (2001) in a set of 48 1 cm^3 samples taken at 5 cm increments along core BC2. Samples were dried in an oven at 45 °C for 24 h. Then they were weighed in a high-precision scale, and burned in a laboratory oven at 450 °C during 5 h. The burned samples were weighed, and LOI was calculated.

3.5. Pollen, other palynomorphs and micro-charcoal

For analysis of pollen, other palynomorphs and micro-charcoal, 47 1 cm^3 samples from BC2 were taken at 5 cm increments along the core. Sample processing followed standard procedures, including sodium pyrophosphate, KOH (to remove organic material), HCl (to remove carbonates) and an acetolysis mixture (acetic anhydride and H_2SO_4 to remove polysaccharides). The pollen fraction, floating on a bromoform-alcohol mixture (gravity 2.0) was decanted and washed. Microscope slides were made with glycerine as a mounting medium. Pollen grains were examined at 400× magnification. For pollen identification we used the pollen and spore reference collection of Institute for Biodiversity and Ecosystem Dynamics, and a variety of pollen morphological literature including Hooghiemstra (1984) and Roubik and Moreno (1991). A minimum of 300 pollen grains were counted in maximally three duplicate microscope slides. Some intervals, mostly characterized by coarse-grained sediments, showed poor pollen preservation and some pollen counts were lower. The lack of information about the recent pollen rain (*e.g.* Moscol-Olivera et al., 2009) and phytoliths (*e.g.* Piperno, 2006) from undisturbed forests makes it difficult to assess how taxa may be under- or over-represented in the fossil pollen spectra, and the effects of change in catchment area due to shifts in river dynamics.

Ten types of fungal spores were systematically counted, including five coprophilous fungi *Sporormiella* (HdV-113), *Cercophora* (HdV-112), *Apiosodaria* (HdV-169) *Sordaria* (HdV-1012), *Podospora* (HdV-368) and *Coniochaeta* (HdV-172) as a signal of the presence of cattle and other herbivores (Schlütz and Shumilovskikh, 2017; van Geel et al., 2003; Gelorini et al., 2011). Other documented non-pollen palynomorphs (NPPs) are indicative of erosion (*Glomus* sp., HdV-1103), humidity levels and the presence of decaying organic matter (*Potamomyces* and *Savoriella*) (van Geel, 2002; Montoya et al., 2010). Fern spores were identified and recorded in all samples. Algal remains were restricted to *Debarya* zygospores. All identified fossils were grouped in the pollen diagram according to their ecological preference. To show changes in the regional and local vegetation, the pollen sum includes woody, herbaceous, and aquatic and wetland taxa. Proportions of fern spores, fungal spores, and other non-pollen palynomorphs were expressed relative to the pollen sum, allowing percentages >100%. For micro-charcoal counting we followed the guidelines of Finsinger and Tinner (2005): counting 200–300 opaque, black, angular charcoal particles. At the start of preparing a pollen sample a tablet with a known number of *Lycopodium* spores was added to allow the calculation of pollen and micro-charcoal concentration values. We used TILIA software version 2.0.41 to plot the results, and CONISS cluster analysis (total sum of squares) to identify zones in the record (Grimm, 1993). All graphs were subdivided using pollen zones, except the phytolith graph.

3.6. Macro-charcoal and plant macro-fossils

For macro-charcoal analysis, 242 samples of 2 cm^3 were collected at 1 cm increments along core BC1. Samples were dissolved in 10% HCL and sieved over a 250 μm mesh. An additional bath in 10% H_2O_2 was applied to samples in which sediment failed to disintegrate in the previous two steps, which occurred mostly in samples between 242 cm and 200 cm. Macrofossils were extracted for each sample.

Charcoal fragments from each sample were isolated and photographed using a Leica KL 200 LED Stereoscope. Photographs of charcoal images were converted to measurements of surface area (mm^2) using ImageJ (Schneider et al., 2012). Fifteen different plant macro-fossil morphotypes were defined and counted throughout the 242 samples. More than 50% of the morphotypes were identified, allowing to better understand changes in the vegetation along the margins of the oxbow lake.

3.7. Phytoliths

For phytolith analysis, 30 1 cm^3 samples were collected at 10 cm increments along the core. Samples were processed following Pearsall (2000), using HCl, H_2O_2, HNO_3, KOH and EDTA solutions. Flotation of phytoliths was achieved by using a bromophrom-ethanol solution (3.0 specific gravity), and mounted in slides using Permount. For phytolith classification we used Piperno (2006), Piperno and Pearsall (1998), Watling and Iriarte (2013), Iriarte et al. (2010), Morcote-Ríos et al. (2016) and Chen and Smith (2013). A minimum of 250 phytoliths were counted per sample, after which an extended scanning was carried out for finding rare or economically important types (Zurro et al., 2016).

4. Results

4.1. Chronology and sedimentation rate

The age model is based on 4 of the 5 radiocarbon ages (Table 1) which show a relatively steady sediment accumulation with intervals of complex sedimentation from 130 to 100 cm (Fig. 3). It shows that the Biajaca record starts at 1100 cal yr BP, when flow energy of the water had decreased to levels that allowed sediments to accumulate. Sedimentation rates remained relatively constant at ca. 1 cm accumulation per 5 years throughout the record. However, the section of the core from 130 to 100 cm, coincident with deposits of coarse silt and sand, possibly shows intrusion of river-borne material explaining the inconsistent radiocarbon age excluded from the model. These rapid changes of the lithological characteristics suggest that the meander served as a temporary drainage system possibly during years with high precipitation and/or under the influence of hurricanes. Such composite sediment deposition in this section of the core is supported by rapid oscillations in pollen percentages of herbaceous and woody vegetation and the absence of macrofossils. Fluvial dynamics likely caused changes in the catchment area and the introduction of river-borne materials in the sediment archive, potentially leading to a loss or disturbance of parts of the sequence during this interval. The age vs. depth model is based on 4 out of 5 radiocarbon dates. The age of the 140–130 cm interval coincides with the encounter between the Old and New Worlds and the sediment column shows there a significant lithological change.

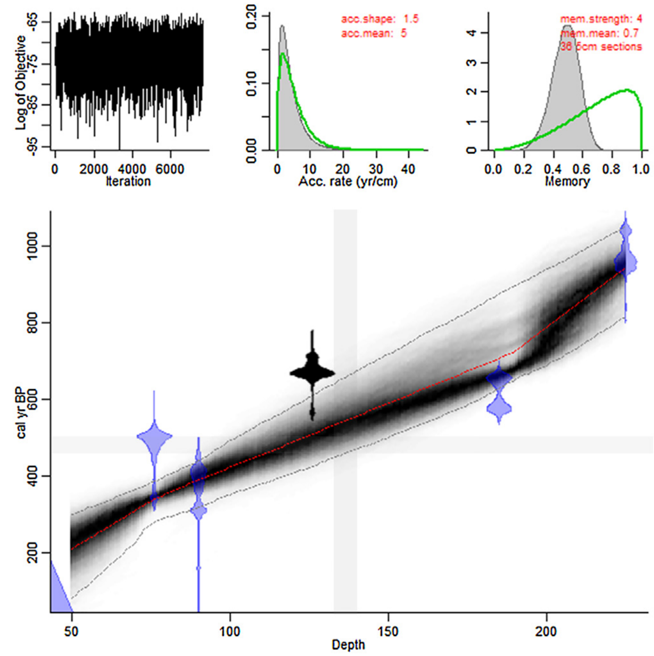

Fig. 3. Age-depth model of core Biajaca produced with BACON (default settings) (Blaauw and Christen, 2011). Markov Chain Monte Carlo iterations are plotted in the upper left panel. Black curves are the prior accumulation rate distributions, and the grey histograms the posterior ones (both in the middle panel). The memory of rate distributions plotted in the upper right panel. Calibrated 14C dates and age-depth model are plotted in the lower panel: blue dates are those used in the model, the black date was left out. Grey area shows 95% confidence intervals. Added vertical and horizontal lines indicate the estimated time of contact at their intersection (~AD 1492).

4.2. Grain size distribution and total organic content

Based on data-visualization of variations in median grain size value and clay-silt percentages, we identified 3 zones in the record of GSDs, supported by TOC values: 240–205 cm, 200–90 cm, and 90–5 cm (Table S1, Fig. 4).

Table 1
Radiocarbon ages and sample specific information.

Depth (cm)	Lab no.	Measured Radiocarbon Age	IRMS δ13C	Lithology
224–225	Beta - 420888	1060 ± 30 BP	−24.8‰	Clay 5041% Silt 4791% Sand 168%
185–183	Beta - 469282	660 ± 30 BP	−23.7‰	Clay 298% Silt 6159% Sand 861%
127–126	Beta - 469283	740 ± 30 BP (sample not used in age model)	−23.0‰	Clay 307% Silt 6569% Sand 424%
90–91	Beta - 420887	290 ± 30 BP	−19.4‰	Clay 6093% Silt 3808% Sand 098%
75–76 cm	Beta - 469284	430 ± 30 BP	−21.9‰	Sand 974%

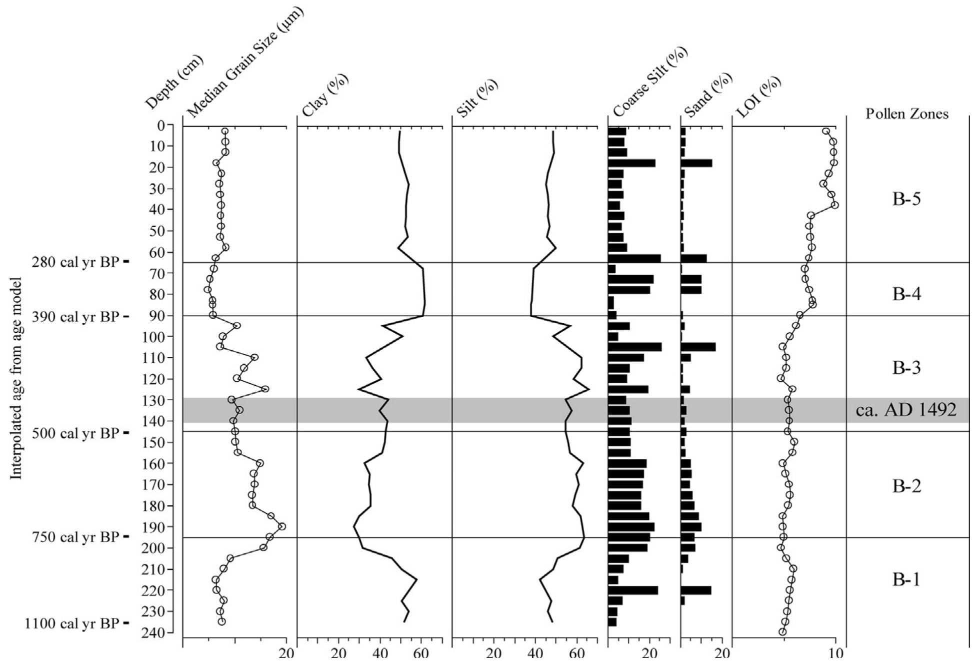

Fig. 4. Records of grain size distributions (μm, %) and organic content by loss on ignition (%).

4.3. Pollen, fern spores and non-pollen palynomorphs

Pollen preservation varied from good to poor throughout the sediment core. Five samples between 195 and 150 cm did not contain enough pollen grains to acquire a meaningful pollen spectrum and were discarded (Table S2). Eleven samples showed a low pollen sum (~150) but were accepted. The diagrams for pollen and NPPs (Figs. 5 and 6) show temporal changes of a selection of the most important taxa. We merged *Cercophora-Apiosordaria* and *Sordaria-Podospora* types in the diagrams due to their joint occurrence throughout the record and similar ecological and morphological characteristics. CONISS cluster analysis recognized 5 pollen zones with zone boundaries at 200 cm (ca. AD 1200; 750 cal yr BP), 150 cm (ca. AD 1450; 500 cal yr BP), 95 cm (ca. AD 1550; 400 cal yr BP), and 65 cm (ca. AD 1650; 300 cal yr BP). A concise description of the pollen zones is provided in Supplementary information Table S3, and in Fig. 5).

4.4. Charcoal

Charcoal analysis revealed that the influx of macro-charcoal varied significantly throughout the sequence. The presence of large and moderate peaks effectively divided the charcoal record into two parts. Values of micro-charcoal concentration closely match the peaks in the record of macro-charcoal influx. The average concentration of micro-charcoal particles is ~100,000 per cm^3 of sediment. (Fig. 7, Supplementary information Table S4).

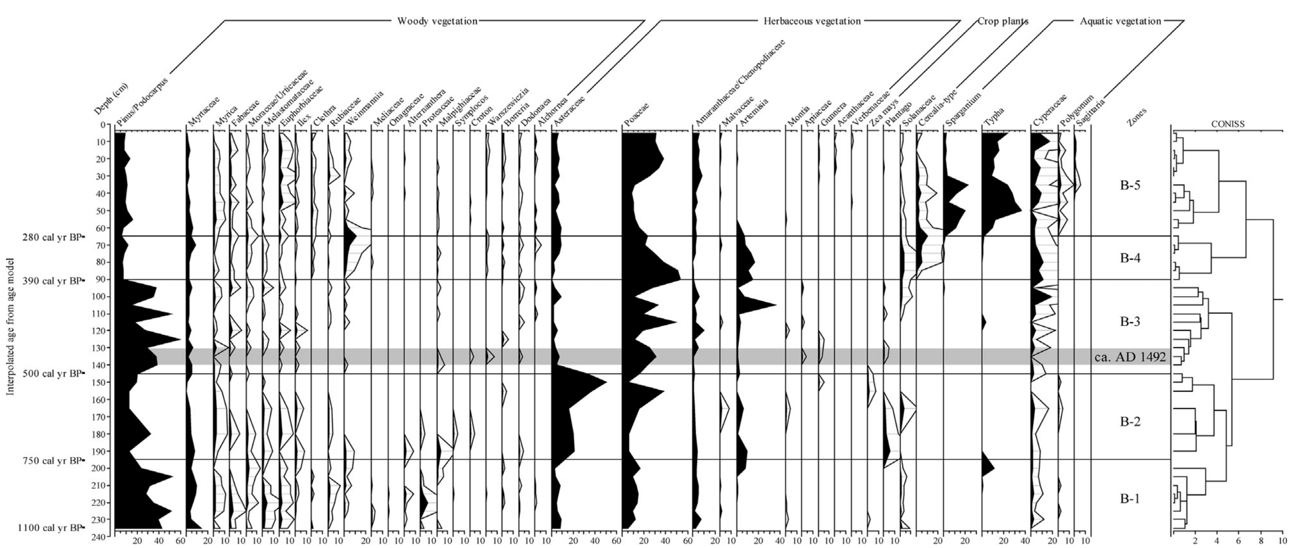

Fig. 5. Pollen percentage diagram of core Biajaca. The taxa reflecting woody vegetation, herbaceous vegetation, and aquatic and wetland vegetation are included in the pollen sum. Exaggeration curve is ×3.

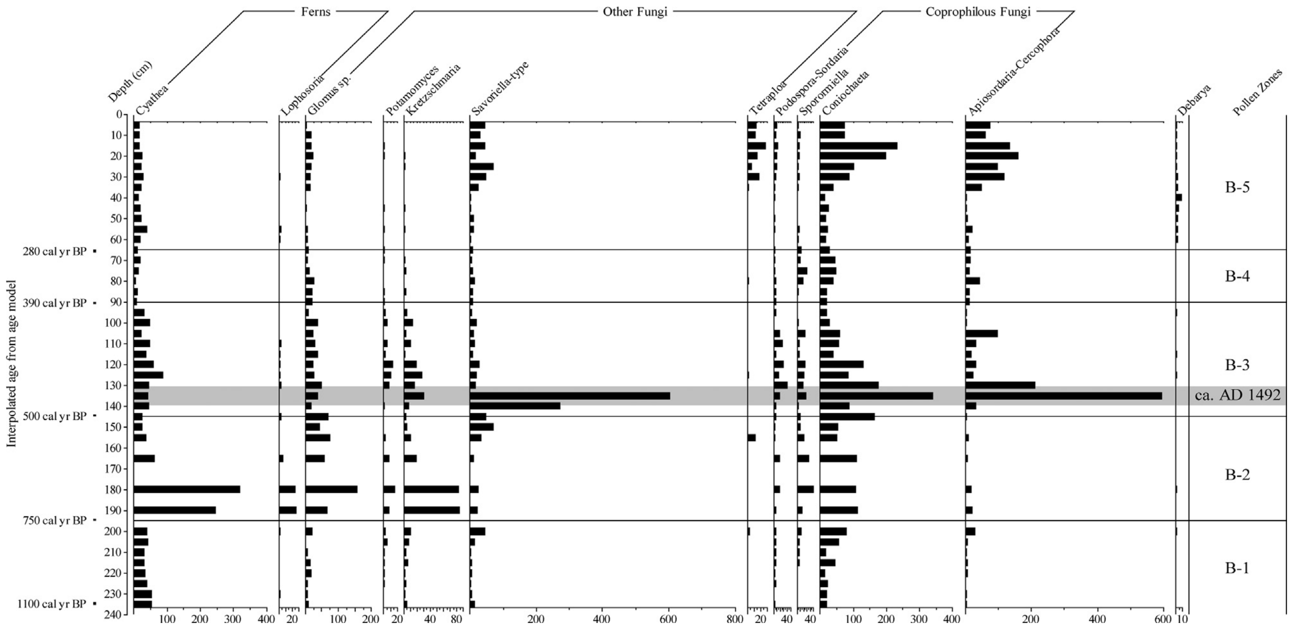

Fig. 6. Percentage histogram of core Biajaca showing fern spores, fungal spores, and algae. Percentages are expressed on the pollen sum and, therefore, may reach values >100%.

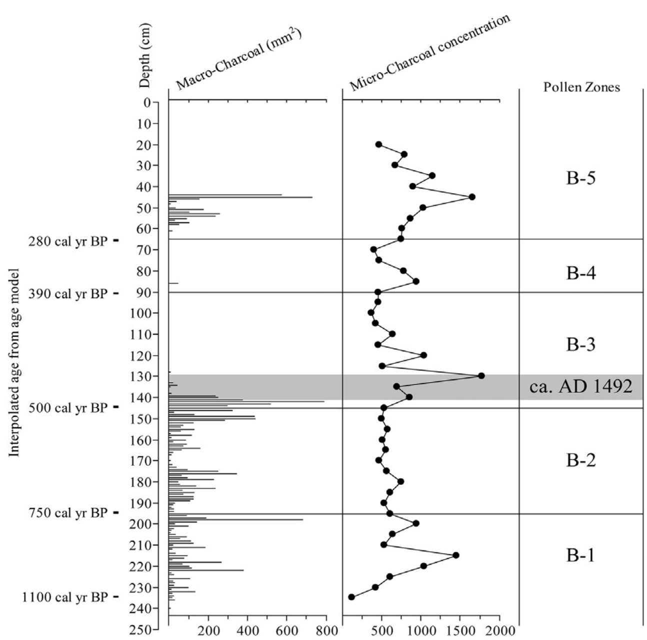

Fig. 7. The records of macro-(mm^2 per cm^3 of sediment) and micro-charcoal (particles per cm^3 of sediment).

4.5. Plant macrofossils

The most common plant macrofossils in the Biajaca sediments belong to the Cyperaceae, Poaceae and Asteraceae families, as well as eight types of unidentified propagules (Plate Plate 1). The presence of distinct seed assemblages and the occurrence of a void interval allowed to identify four distinct plant macrofossil assemblage zones based on data-visualization (Fig. 8). Unknown plant macrofossils received a code (BIA-X) in order of appearance, starting from the bottom of the core. A concise description of the plant macrofossil zones provided in Supplementary information (Table S5).

4.6. Phytoliths

Four main phytolith zones were recognized by CONISS cluster analysis. Phytolith presence is expressed as a percentage of the total number of phytoliths which were grouped into 5 main sets: (1) Poaceae short-cell, (2) Poaceae long-cell (mainly Bulliform types), (3) Zingiberales, (4) palms (5) arboreal (Fig. 9, Supplementary information Table S6). In the environmental reconstruction, the development of the palm component of the forest and local grass systematics gained substantially by the analysis of phytoliths. For instance, while very few palm pollen grains were identified, the phytolith record revealed their local presence throughout the record.

4.7. Meander abstraction, past fluvial dynamics and vegetation change

4.7.1. Period 1: AD 850–1200 (1100–750 cal yr BP)

Based on the GSD and LOI records, between AD 850–1200 (1100 and 750 cal yr BP), the meander of the Yaque River under study lost its drainage function and became isolated from the main river course. An open body of water formed, and waterside vegetation was scarce, explaining the low organic content of the sediments (Fig. 4). Presence of Characeae oospores is indicative of calcareous waters which were likely not polluted (Wade, 1990) (Fig. 6). The pollen record shows a relatively high taxonomic diversity including taxa characteristic of wet (*e.g. Weinmania,* Proteaceae, *Croton*) and dry (*e.g.* Fabaceae, Euphorbiaceae) conditions reflecting mixed (seasonal) forest (Fig. 5). Some of these arboreal taxa are continuously present in the record, such as *Pinus-Podocarpus*, Myrtaceae, *Myrica*, Euphorbiaceae, Fabaceae, *Weinnmania,* and form the matrix of the hardwood forest. Other taxa, such as Proteaceae, disappeared after AD 1200 from the pollen spectra reflecting an impoverishment of the forest. Pollen grains of *Croton*, Meliaceae, Malpighiaceae and *Ilex,* reflecting large forest trees, were particularly abundant between 850 and AD 1250 (1100 and 700 cal yr BP). The phytolith record is in support of a forested landscape by showing the dominance of palms, especially abundant until ca. AD 1150 (800 cal yr BP) (Fig. 9). The presence of *Cyathea* tree ferns is in support of relatively dense forest with abundant shade and humid understory in the interior of the island. Seeds of *Eupatorium* sp. and cf.

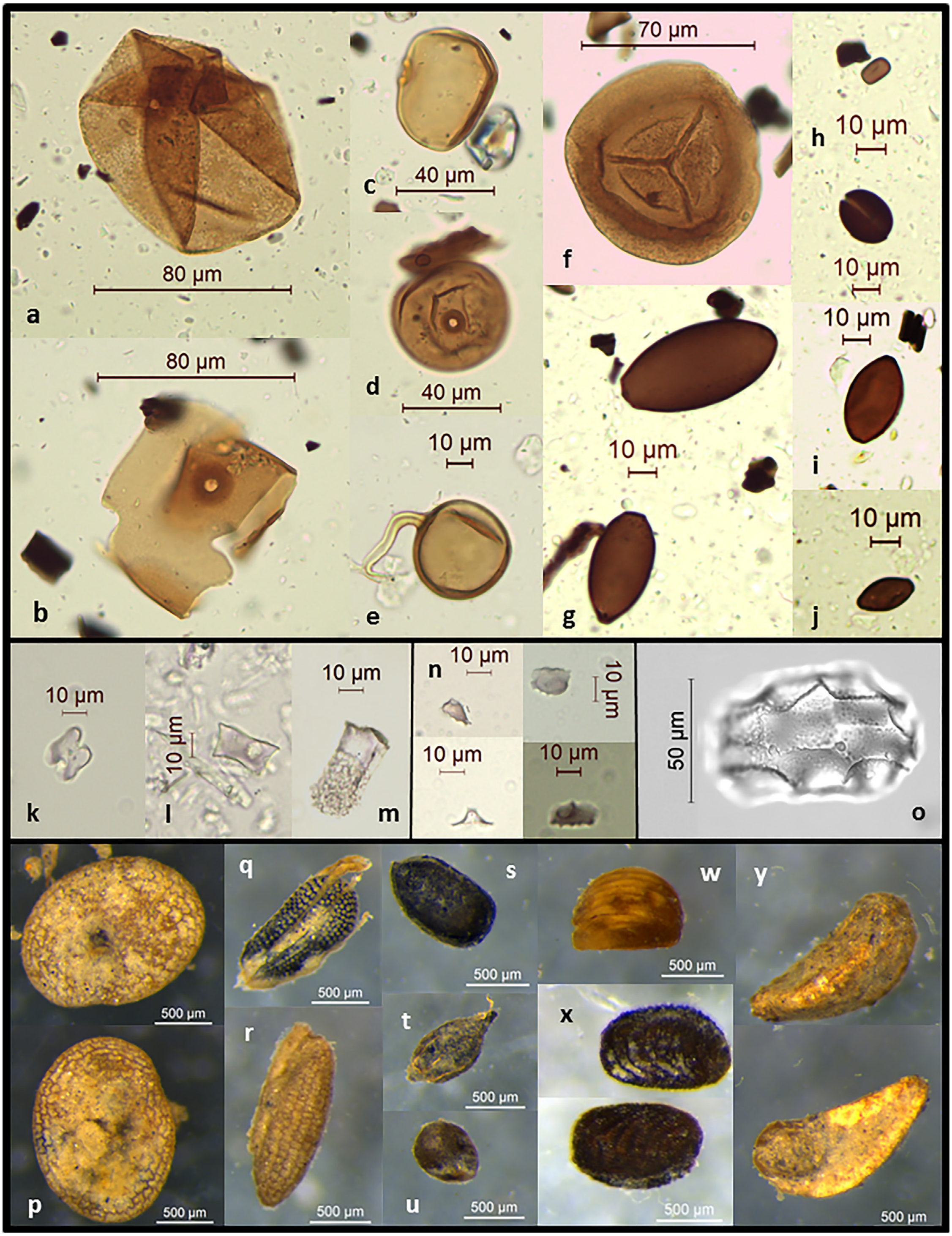

Plate 1. Illustration of selected pollen, non-pollen palynomorphs, seeds, and phytoliths documented in Laguna Biajaca: **Pollen**: a. *Zea mays*, level 145 cm; b. *Zea mays*, level 155 cm; c. and d. Cerealia-type, level 80 cm; **NPPs**: e. *Glomus* sp.; f. *Lophosoria*; **g.** *Podospora*-type; h. *Sporormiella*; i. *Sordaria*-type; j. *Cercophora*/*Apiosordaria*-type; **Phytoliths**: k. Cross Var. 1; l. Wavy-top rondel; m. *Calathea* sp.; n. Musaceae; o. *Cucurbita* sp.; **Seeds:** p. *Solanum* sp.; q. BIA-1; r. BIA-2; s. BIA-3; t. BIA-5; u. BIA-6; w. BIA-7; x. BIA-8; y. BIA-4.

Asteraceae found throughout this period indicate that the borders of the abandoned meander were likely covered by a rich herbaceous vegetation. Macro- and micro-charcoal records suggest that small fire events occurred regularly in the area around the site (Fig. 7).

4.7.2. Period 2: AD 1200–1450 (750–500 cal yr BP)

Between AD 1200–1450 (750 and 500 cal yr BP), the GSD record suggests that the meander was periodically reactivated. The higher energy levels are reflected in the silt-rich composition of the sediment deposits (Fig. 4). The increase of median sediment grain sizes means that pollen grains are easily corroded, pollen preservation is poor and organic matter content low in this interval. Increased precipitation after ca. AD 1200 (ca. 750 cal BP) (Beets et al., 2006; Lane et al., 2009) and forest clearing may have contributed to the periodical return of a drainage function. The pollen spectra show a progressive increase of Asteraceae and

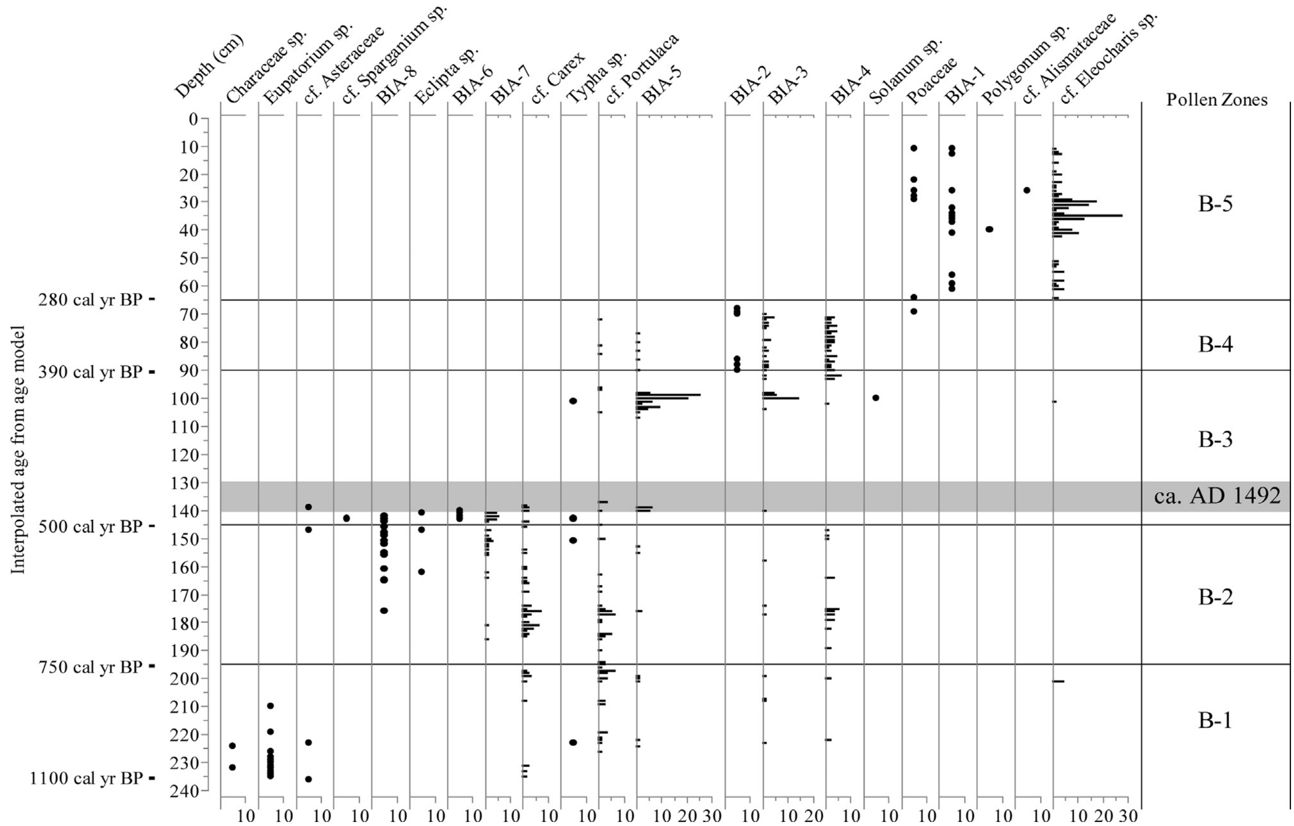

Fig. 8. Plant macrofossil diagram. The length of the bars reflects the number of fossils.

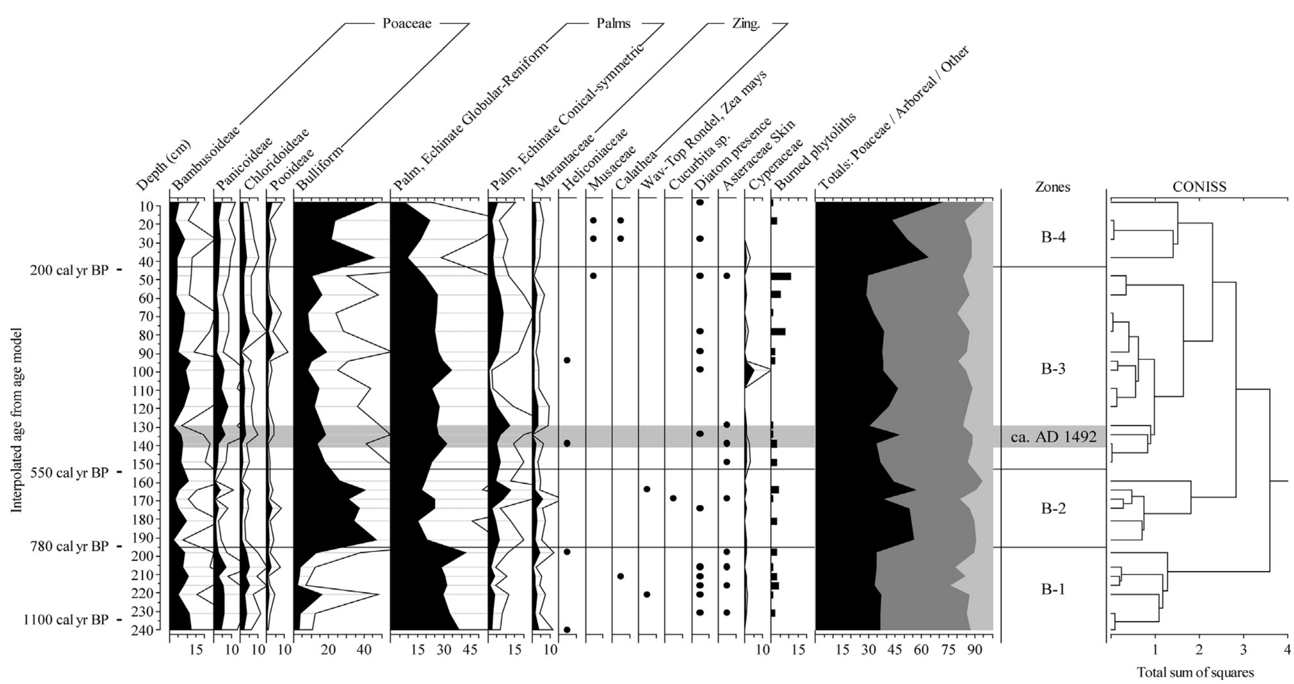

Fig. 9. Phytolith percentage diagram. Exaggeration curve is ×3.

Poaceae, and a decline of forest taxa, suggesting that the landscape became more open (Fig. 5). The concentration of NPPs increased during this period: high percentages of *Lophosoria* fern spores, successional species in disturbed areas (Kennedy et al., 2005; Tryon and Tryon, 1982), and fungal spores of *Glomus* are indicative of erosion in the catchment (van Geel et al., 2011; Almeida-Leñero et al., 2005) (Fig. 6). Peaks in the abundance of *Sporormiella* and *Coniochaeta* reflect wet conditions, and the presence of herbivores around site Biajaca (Gelorini et al., 2011). Presence of the wood-rot fungus *Kretzschmaria* suggest decaying organic material and/or wood (van Geel et al., 2013) near the water body. Similarly, presence of *Potamomyces* fungal spores are indicative of wet-to-damp conditions and the presence of submerged decaying wood (Schlütz and Shumilovskikh, 2013). The macrofossil record shows that the margins of the gradually infilling meander became enriched with plants such as *Portulaca*, *Carex* and *Eclipta* (Fig. 8). The phytolith record shows a decrease in woody vegetation and an increase of Poaceae Bulliform cell-types in relation to Poaceae short-cells (Fig. 9). Based on the findings of Bremond et al. (2005) in East Africa and Borba-Roschel et al. (2006) in Brazil, the dominance of Bulliform cell-types in Poaceae can be attributed to water-adapted grasses. Humid conditions are also supported by an increase in the abundance of Zingiberales phytolith types, such as Marantaceae and Heliconiaceae, characteristic of margins and humid under-story settings in wet forest (Piperno et al., 2007). Despite indicators of humid conditions, the charcoal record shows a continuous and abundant human use of fire close to Laguna Biajaca as well as more widely throughout the Cibao Valley (Fig. 7).

4.7.3. Period 3: AD 1450–1550 (500–400 cal yr BP)

Three main peaks of coarse grain sizes during the period from ca. AD 1450–1550 (ca. 500–400 cal yr BP) show that the meander was integrated in the drainage of the river during flooding events (Fig. 4). The pollen record shows alternative high and low proportions of Poaceae and *Pinus-Podocarpus*, coincident with peaks in grain size, coarse silt and sand. This, together with the absence of macro-fossils and a surprisingly old bulk sediment radiocarbon age of the sediment at core depth 127 cm, suggests that the river could have redeposited old material in the sediment matrix during flooding events. Despite pronounced variability in the pollen record, an overall decline of *Pinus-Podocarpus* and an increase of Poaceae can be identified, indicating a transition towards an open landscape, as well as a change from a regional catchment signal to a more local swamp signal. Cyperaceous vegetation replaced asteraceous vegetation, reflecting expansion of swamps. Heliophytic taxa of open forest with pioneer qualities, such as *Gunnera* and Apiaceae, are indicative of progressing forest clearance (Fig. 5). Increasing abundance of NPPs (*Savoryella*-type on decaying wood) support human impact, and rapidly increasing proportions of spores of coprophilous fungi are indicative of increasing numbers of herbivores (Fig. 6). The cessation of macro-charcoal influx in the meander could also be related to river activity, but its sustained absence in later periods and the low concentrations of micro-charcoal suggest that fire was absent from the vicinities of the site in this period (Fig. 7). The phytolith record shows the dominance of Panicoideae and Chloridoideae short-cells, grasses characteristic of agricultural landscapes (Piperno et al., 2007).

4.7.4. Period 4: AD 1550 to ∼1700 (400–275 cal yr BP)

Between AD 1550 and 1700 (400 and 250 cal yr BP) the meander became increasingly covered by swamp vegetation and filled up with small-grained (clay) organic rich sediments (Fig. 3). This was followed by a dramatic increase of *Artemisia* (pioneers on open soils) suggesting that forests had been intensively cleared. The increase of the record of Solanaceae is difficult to interpret, as it may reflect different components of the landscape such as pioneering vegetation in almost clear-cut forest, herbs in the swampy vegetation, or cultivated plants (*e.g.* tomato, tobacco or potato) (Fig. 5). The macrofossil record also reflects rapid changes in the vegetation: seed types BIA-2, 3, 4, and 5 (also present in previous centuries in lower quantities) became dominant (Fig. 8). The macro-charcoal record indicates that there were no more local fires during this century (Fig. 7).

In the period between AD 1650–1750 (300 and 200 cal yr BP) GSDs show clay-rich deposits indicative of lake conditions with standing water; the meander was now definitively isolated from the Yaque River drainage system (Fig. 3). Signals in the pollen record pointing to an open landscape became even more abundant: high proportions of Poaceae, abundant 'meadows' with *Artemisia*, and a decrease of arboreal pollen. *Pinus-Podocarpus* became less abundant in the forest and remaining arboreal elements are Myrtaceae, W*einmannia*, *Clethra*, Fabaceae, Rubiaceae (*Warszewiczia* in particular) and Euphorbiaceae, again reflecting a mixed forest with taxa characteristic of wet to dry habitats (Fig. 5). The macrofossil and phytolith records show continuity in relation to the previous century with the exception of a decrease in palms in the second half of the century. Fire rarely occurred in the area adjacent to the meander, possibly because this area had been cleared already, but the micro-charcoal record suggests that fire was common in the Cibao Valley.

4.7.5. Period 5: CE 1750 to present-day (200 to −50 cal yr BP)

During the period from AD 1750 to present-day (200 to −50 cal yr BP), the marsh filled up with clayish sediment and became eutrophic, stimulating swamp vegetation and development of organic rich sediments. Dominant waterside and aquatics are *Typha*, *Sparganium*, *Sagittaria*, *Polygonum*, and the alga *Debarya*. The abundance of *Sparganium* in the first part of this period and its posterior decline could reflect increasing eutrophication (Medeanic and Dillenburg, 2005) (Fig. 5). Assemblages of spores of coprophilous fungi show that during the last two centuries large herbivores were continuously present (Fig. 6). Taxa with pioneer qualities, such as *Warzewiczia*, *Borreria*, *Alchornea*, Verbenaceae and Acanthaceae appear in the pollen record and point to degraded forest. The plant macrofossil record includes seeds of Poaceae, the aquatics *Polygonum* and Alismataceae, and *Eleocharis* characteristic of watersides (Fig. 8). The appearance in the record of Musaceae (banana) phytoliths is matched by a decrease of palms in the forest and woody vegetation around the site (Fig. 9). This forest decrease coincides with a peak in macro- and micro-charcoal suggesting the use of fire at a local and regional scales. During the last two centuries there is no evidence of local fire.

5. Discussion: culture-environment dynamics

High temporal resolution multi-proxy analyses of records spanning the last millennia have the potential to improve understanding of the diverse drivers of change and feedback mechanisms between social and natural phenomena (Dearing et al., 2015). Explaining landscape change as a process of human and environmental factors requires the integration of biotic and abiotic proxies in sediment records with archaeo-historical data. It is also central to pay special attention to fire history and the direct and indirect effects of economic activities in the landscape (Bush et al., 2016; Gosling et al., 2017). In this study, the identification of maize pollen grains (Lane et al., 2008), maize-cob phytoliths and domestic *Cucurbita* sp. phytoliths (Piperno, 2006; Iriarte et al., 2010) constitute direct evidence of pre-Colonial economic activities (Plate). In colonial times, agriculture relates to the presence of Solanaceae and Cerealia-type pollen, as well as Musaceae phytoliths reflecting banana cultivation.

Various climatic regimes have been documented in Hispaniola (Table 2): from ca. AD 350 to 1050 (ca. 1600 to ca. 900 cal yr BP) increasing aridity marked by drought events; a period of decreasing aridity to relative wetness from ca. AD 1050 to 1250 (900 to 700 cal yr BP); relatively moist conditions from ca, AD 1250 to ca. 1600 (ca. 700 to 350 cal yr BP); and since ca. AD 1600 (ca. 350 cal yr BP) relatively dry conditions. In contrast to other paleoenvironmental records from Hispaniola, in site Biajaca human influence dominates throughout the record; Demographic changes related to the encounter between the Old and the New World human populations and the introduction of crop plants create sharp contrasts in the record, while shifts in the

Table 2
Climate and human-driven environmental changes as seen in selected paleoecological records in Hispaniola and the circum-Caribbean area (after Lane et al., 2009).

Period	Regional climate	Other Paleo-records from Hispaniola	Circum-Caribbean Paleo-records
AD 350–1050 (1600–900 cal yr BP)	Increasing aridity	- Las Lagunas: Decrease in fire-return intervals, decrease lake levels, drought events 1200–1000 yr BP (Lane et al., 2009). - Lake Miragoane: Depressed charcoal values but an increase of dry forest taxa (Higuera-Gundy et al., 1999).	- Cariaco Basin: decrease in regional precipitation (Haug et al., 2001). - Mayan Terminal classic collapse linked to repetitive drought events (Hodell et al., 2001).
AD 1050–1250 (900–700 cal yr BP)	Decreasing aridity	- Las Lagunas: Human-driven deforestation and erosion, maize pollen (Lane et al., 2009). - Lake Miragoane: High charcoal values linked to the arrival of agriculturalists (Higuera-Gundy et al., 1999).	
AD 1250–1600 (700–350 cal yr BP)	Relatively moist	- Las Lagunas: Ecosystem recovery after human impacts (Lane et al., 2009). - Lake Miragoane: 500 yr BP maize pollen (Higuera-Gundy et al., 1999).	- Cariaco Basin and Puerto Rico: increased precipitation linked to higher sea surface temperatures (Haug et al., 2001; Nyberg et al., 2002).
AD 1600 to present-day (350 cal yr BP to present- day)	Arid	- Las Lagunas: Oxygen isotopes show increased aridity and shallow lake levels (Lane et al., 2009). - Laguna Saladilla: 44 cal yr BP Charocal peak indicating deforestation (Caffrey and Horn, 2015)	- Cariaco Basin: very dry conditions indicated by metal concentrations (Haug et al., 2001). - Aguada X'caamal, Mexico: decrease lake level and increase aridity (Hodell et al., 2005)

sequence are not directly associated with climatic changes. The earliest part of the record shows an already managed environment, but clearings were limited and a large proportion of original vegetation was still intact. All lines of evidence combined point to three main moments of change as shown in Table 3 and Fig. 10. Landscape change during the last millennium in the Cibao Valley was driven by human impact and re-organizations of trajectories of the Yaque River to which increased precipitation and tropical storms potentially contributed.

5.1. Late-Ceramic Age: AD 1000–1492 (zones 1 & 2)

Based on ethnohistorical and increasing archaeological evidence, the Late Ceramic Age can be defined as a period of colonization of the inner valleys of Hispaniola by full horticulturalists who created and maintained complex socio-political relationships (Veloz Maggiolo, 2003; Wilson, 1990). The occurrence of local and regional fires and the local presence of crop plants during the Late Ceramic Age are consistent with substantial human activity in the Cibao Valley during the centuries prior to European colonization. This confirms previous results from western Hispaniola (Higuera-Gundy et al., 1999) and the Cordillera Central (Lane et al., 2008). The first pollen and phytoliths of maize in the sequence date to around AD 950 (1000 cal yr BP). Around AD 1100 (850 cal yr BP) rhizome cylinder phytoliths of *Calathea* sp. could indicate the cultivation of the economic species known as lerenes (*Calathea allouia*), though these phytoliths could also have been produced by a wild species (*Calathea lutea*) associated to the understory of humid forests in the Neotropics (Chandler-Ezell et al., 2006; Santiago Brilhante et al., 2013). As this evidence is scarce compared to a later pre-Colonial period, it possibly reflects small-scale crop production for local use. The record suggests that pre-Colonial economic activities had opened the landscape at many places and favored erosion.

Ca. AD 1150 (800 cal yr BP), progressive forest degradation and the reorganization of the river course had profound impacts on the local and regional environment. The main drivers of this transformation were the change in the fluvial course and the increasing erosion linked to human-driven deforestation, reflected by the first micro- and macro-charcoal peaks in the record. One main feedback loop between the increased precipitation in wet seasons and the use of fire for forest-clearing by indigenous people could have led to the vulnerability of the local area to erosion caused by seasonal floods. A particularly intense fire event may have prompted a rapid change in local conditions towards an open, fern-rich marshy landscape. The increase in humidity indicators and the appearance of water-adapted grasses rapidly followed.

The first direct evidence of agriculture in this period is the presence of phytolith of domesticated squash (*Cucurbita* sp.; Cucurbitaceae) ca. AD 1250 (700 cal yr BP), followed by the sustained influx of maize pollen grains until AD 1450 (500 cal yr BP). Crop fields may have been located close to the meander and could reflect the pre-Colonial practice of inter-cropping. According to ethnohistorical sources, it is likely that these agricultural fields were planned in the form of gardens -*conucos*- or raised mounds, and held other staple crops such as manioc or cassave (*Manihot esculenta*) and sweet potato (*Ipomoea* sp.) (Fernández de Oviedo, 1851; de Las Casas, 1875). The proximity to the archaeological site of Los Indios (<2 km), which might have been an important node in the pre-Colonial route from the valley to the northern coast, allows a connection to be proposed between the cultivation of the area and occupation of the site. The charcoal record indicates persistent burning from ca. AD 1150 (800 cal yr BP) to ca. AD 1450 (500 cal yr BP), with special intensity at the beginning and the end of this

Table 3
Summary of cultural and environmental transitions inferred from the multi-proxy record of Laguna Biajaca in the Cibao Valley, Dominican Republic.

Transition threshold	Fast processes	Long-term processes	Potential drivers and feedbacks	Stabilization	Evidence
Ca. AD 1150 (800 cal yr BP)	Reorganization of the river course and increasing erosion	Forest degradation	Anthropogenic fires, deforestation, intensification of seasonal floods	Enriched soils suitable for pre-Colonial cultivation	Decrease of forest taxa, increase in humidity indicators, arrival of water-adapted grasses
Ca. AD 1500 (450 cal yr BP)	Arrival of Old World domesticated animals and rapid decline of fire-use	Weeding processes and expansion of parches of pioneer taxa	Depopulation, collapse of the indigenous economic system	Establishment of the first Colonial crop cultivation	Change in abundance of coprophilous fungi and charcoal, dominance of weeds and pioneer taxa
Ca. AD 1700 (250 cal yr BP)	Meander sediment infill, increase in fire-use	Deforestation and lake eutrophication	Intensive human land-use, expansion of monocultures	Present-day landscape	Abundance of aquatics and wetland species, coprophilous fungi and agricultural indicators

period. This fire signal could be related to the use of slash-and-burn horticulture, a practice argued to be central to the Taíno economy during the Late Ceramic Age (Chanlatte Baik, 2003; Gebelein, 2011). This contrasts other landscape management strategies in the Neotropics, such as the fire-free land-use of savannas in Amazonia during pre-Colonial times (Iriarte et al., 2012).

5.2. Contact and early-colonial period: AD 1492–1600 (zone 3)

Ca. AD 1500(450 cal yr BP) profound culture-environmental change in the Cibao Valley derived from the dramatic encounter between indigenous peoples and European colonizers, which likely developed at different rhythms in different areas. The sudden depopulation of the Cibao Valley meant the collapse of the indigenous economic system and the dawn of a new era of land management. Immediate environmental imprints - or fast processes- included a change in the NPP record marked by the occurrence of peaks of coprophilous fungi (*Podospora-Sordaria* types, *Cercophora-Apiosordaria* types, *Coniochaeta* and to a lower extent, *Sporormiella*) and *Savoriella*-type ascospores (Fig. 6). Also, macro-charcoal values around these depths show the absence of charcoal deposition at the local scale, which contrasts with previous significant fire events. The cease of fire-use in the vicinity of the Biajaca site suggests that neighboring agricultural fields were abandoned due to economic change towards a cattle-grazing economy. The decrease of anthropogenic indicators and the emergence of new woody vegetation components in the landscape until around AD 1550 (400 cal yr BP) might reflect the response time between the indigenous demographic and socio-political collapse and the advent of significant numbers of European migrants and enslaved labor force.

The conjoined action of domesticated animals and the European settlers led to long-term processes of landscape transformation. In particular, the increase in the presence of *Artemisia* points to progressive forest clearing and the subsequent substitution by patches of taxa with pioneer strategies. The action of cattle likely favored pioneer and weedy taxa, spreading the seeds that grew in the river-disturbed open areas along the Yaque River, and perhaps, in the abandoned *conucos* (Watts, 1987). Nevertheless, the influence of periodic river deposits prevents a clear ordering in the sedimentary archive of these short-term processes. The overall decrease of *Pinus-Podocarpus* could be related to forest degradation due to deforestation, but also the change from open water to marsh may have contributed to a change in the fossil pollen spectra. Planned archaeological work in surrounding archaeological sites could help to better understand the timing and effects of the abandonment of the indigenous habitation sites, as well as those linked to the growth of colonial urban hubs such as the city of Mao.

5.3. Late-colonial period: AD 1600-present day (zones 4 & 5)

The colonial occupation of the vicinities of Laguna Biajaca led to the implementation of European agricultural techniques and crops, while the recent occupation is marked by the adaptation of the valley to cattle grazing and extensive monocultures of mainly banana and rice, for which recently extensive hydrological systems have been built. The abundance of Solanaceae and Cerealia-type pollen ca. AD 1550 (ca. 400 cal yr BP) indicates the establishment of European crops in the river valley. Although Solanaceae pollen is also complemented by the presence of a *Solanum* sp. seed, the species remains unclear, and it is possible that our evidence reflects crop plants (tomato, tobacco, potato) or was produced by a wild species.

Ca. AD 1700 (250 cal yr BP), Laguna Biajaca experienced the effects of intensive human land-use: grazing caused deforestation and eutrophication of the stagnant water bodies, and expanding

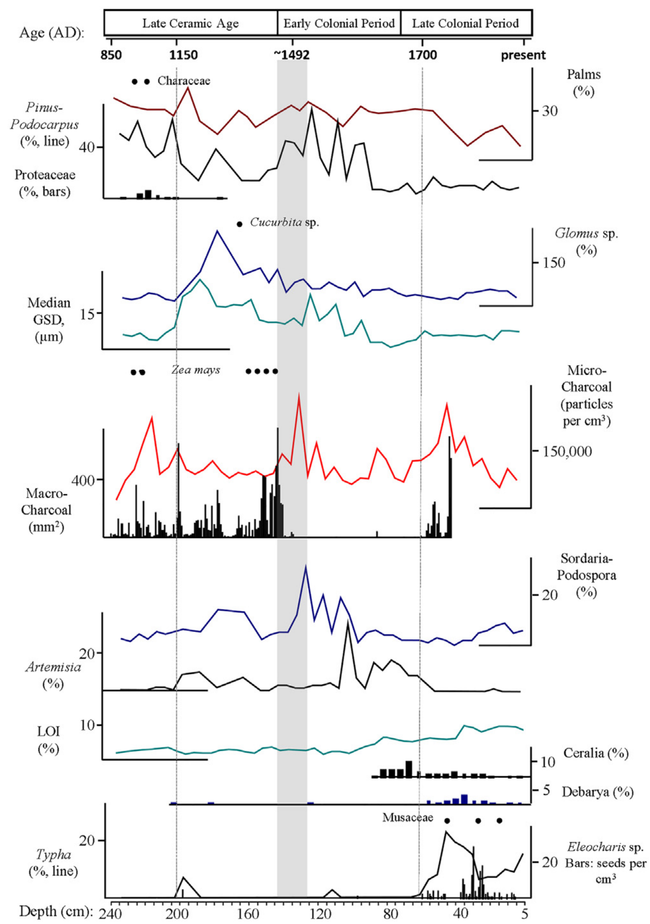

Fig. 10. Multi-proxy diagram of the main culture-environmental transitions during the last 1100 years in the central Cibao Valley. Line colors: Black, pollen; Blue, NPP; Brown, phytoliths; Purple, sedimentology; Red, micro-charcoal. Bar colors: Black, pollen-charcoal-seeds; Blue, NPP. Dots indicate the presence of pollen/phytoliths.

monocultures caused deforestation and, recently, excessive use of pesticides. Indeed, abundant aquatics and the alga *Debarya* suggest a process of sediment accumulation and human and livestock-induced eutrophication of the lake. The increasing influx of macro-charcoal, peaking dramatically ca. AD 1750 (200 cal yr BP), and the appearance of Musaceae phytoliths in the record seem to reflect an intensive land-clearing process for the creation of banana plantations. It is plausible that humans have actively drained the oxbow lake after the definitive isolation of the meander from the active river course. Using the area for grazing must have triggered the development into a wetland, favoring waterside and aquatic plants (*Typha, Polygonum, Eleocharis*) over others (*Sparganium*) and eutrophication. The subsequent sudden decrease of *Sparganium* coincides with an increase in coprophilous fungi, as well as *Tetraploa* spores -with various possible aquatic and marshy host-plants- indicating shifts in water conditions and the establishment of grazing areas. Local humid environments prevailed in the lake area, while surrounding areas were cleared with fire for the establishment of monocultures. This landscape has prevailed until the present day, in which banana and rice monocultures dominate a great part of the central Cibao Valley along the Yaque River.

5.4. Paleoecology, conservation and heritage

This study focused on how human action and diverse environmental factors shaped the landscape of the central Cibao

Valley during the last millennia. The environmental record from Laguna Biajaca improves our understanding of the different strategies of landscape management employed by pre-Colonial indigenous communities and European colonizers and its impact on the environment. It also stresses the need to combine diverse lines of evidence in order to both generate comprehensive hypotheses and understand how social and natural aspects of landscapes interact through time.

Currently, climate change, aridification (UNEP, 2013) and overexploitation are main vulnerabilities in Hispaniola's landscape. The expected increase in drought frequency (Bates et al., 2008) and tropical storm occurrence potentially have devastating effects in the coastal and interior zones (Knutson et al., 2010). Erosion, land degradation and loss of productivity are especially affecting the dry Haiti-Dominican Republic border zone, which is particularly vulnerable to extreme weather events (UNEP, 2013).

By assessing the degree of ecological change related to diverse cultural transformations in the Cibao valley, our results show the long and short-term variability of natural systems. The integration of different regional records can be used as guidelines for conservation managers seeking to restore Hispaniola's landscapes (Nogué et al., 2017). For instance, the discouragement of slash and burn practices, the implementation of agroforestry, and the restoration of pre-Colonial forests in the northern Dominican Republic could have long-term benefits for biodiversity and local communities. This could also be beneficial to better prevent erosion and changes in the river course. While this study focused on environmental change, further integration of archaeo-historical and paleoenvironmental studies will improve our understanding of the legacies of the past that are still present in our current cultural landscape (*e.g.* Foster et al., 2003; Pesoutova and Hofman, 2016).

6. Conclusions

Multi-proxy analysis of a 240 cm long sediment core from Laguna Biajaca at the heart of the Cibao Valley reflects environmental change during the last 1100 years and reveals changes from pre-Colonial to post-Colonial times. Due to its location along the Ruta de Colón, this sediment-filled meander witnessed some of the most fundamental cultural transformations of the last millennium on the island. This nutrient-rich floodable locus for horticulture, agriculture, grazing and wood collection shaped the local lifeways of pre-Colonial and Colonial migrants. Results show that the studied meander became isolated from the Yaque River's course and developed into a clear-water lake in a palm-rich forested landscape. Changes in forest composition and spectra of fungal spores between AD 1150–1250 (800 and 700 cal yr BP) were linked to decreasing local fluvial activity and human-driven deforestation. The ever-changing drainage pattern left abundant marches in the Cibao Valley, reflected in the establishment of communities of herbaceous taxa, and the decrease of woody vegetation. While anthropogenic impacts on the landscape were relatively small during pre-Colonial time, from AD 1250 to 1450 (700 to 500 cal yr BP) indigenous people periodically used fire, probably within a slash and burn system, to cultivate economic plants like maize and squash (*Cucurbita* sp.). A few decades after the arrival of the Europeans, horticultural activities ceased and the indigenous sites surrounding the lake were largely abandoned. Contemporarily, domesticated animals from the Old World were introduced. In the Early Colonial period, patches of land in the central Cibao Valley were cleared in order to create fields for European cultivars. By that time, the oxbow lake had become definitively isolated from the drainage system and aquatics started the process of terrestrialization. During the last centuries cattle breeding caused eutrophication of the lake and much forest in the Cibao Valley was burned to facilitate monocultures, such as banana plantations. This environmental history is relevant to allow for a historically contextualized assessment of present-day socio-economic problems related to the increasing landscape deterioration, as well as to enhance the value of cultural landscape as a heritage, by shedding light into indigenous and colonial land-use legacies.

Author's contribution

CLH and MLPH designed the Nexus Project and the present study, HH, ACB, MLPH, MF and JUH performed the exploration in the field and collected the sediment cores. ACB analyzed all samples under supervision of HH for pollen, BvG for fungal spores, MHF for plant macrofossils, MP for sediment analysis, TD for loss on ignition, JPJ for phytoliths, WDG and CM for charcoal, and MLPH and CLH for radiocarbon samples. Archaeological field registry was done by JHU and EHM, and the maps were done by EHM. HH supervised the project and paper writing. ACB drafted the text with substantial revisions by HH, and all authors contributed equally to prepare a final draft.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ancene.2018.05.003.

References

Almeida-Leñero, L., Hooghiemstra, H., Cleef, A.M., van Geel, B., 2005. Holocene climatic and environmental change from pollen records of lakes Zempoala and Quila, central Mexican highlands. Rev. Palaeobot. Palynol. 136, 63–92.
Altieri, M., Nicholls, C.I., 2001. Ecological impacts of modern agriculture in the United States and Latin America. In: Solbrig, O.T., Paarlberg, R., Di Castri, F. (Eds.), Globalization and the Rural Environment. Harvard University Press, Cambridge, Mass, USA, pp. 121–135.
Anderson-Córdova, K.F., 2017. Surviving Spanish Conquest: Indian Fight, Flight, and Cultural Transformation in Hispaniola and Puerto Rico. University of Alabama Press, Tuscaloosa, USA.
Armstrong, D.V., Hauser, M., Knight, D.W., Lenik, S., 2009. Variation in venues of slavery and freedom: interpreting the late eighteenth-century cultural landscape of St. John, Danish West Indies using an archaeological GIS. Int. J. Hist. Archaeol. 13, 94–111.
Arranz, L., 2006. Cristóbal Colón. Diario de Abordo. Biblioteca Edaf., Madrid.
Arrom, J.J. (Ed.), 2001. Fray Ramón Pané: Relación acerca de las antigüedades de los indios. undécima edición Siglo XXI Ediciones, México.
Artigas, R.C., Batlle, J.R.M., Del Olmo, F.D., 2012. Desarrollo sostenible y medio ambiente en República Dominicana: medios naturales, manejo histórico, conservación y protección. CSIC Press, Madrid.
Bates, B., Kundzewicz, Z., Wu, S. (Eds.), 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva, pp. 210.
Beets, C.J., Troelstra, S.R., Grootes, P.M., Nadeau, M.J., Borg, K., de Jong, A.F.M., Hofman, C.L., Hoogland, M.L.P., 2006. Climate and pre-Columbian settlement at Anse à la Gourde, Guadeloupe, Northeastern Caribbean. Geoarchaeology 21, 271–280.

Blaauw, M., Christen, J.A., 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Anal. 6, 457–474.
Borba-Roschel, M., Alexandre, A., Varajao, A.F.D.C., Meunier, J.D., Varajao, C.A.C., Colin, F., 2006. Phytoliths as indicators of pedogenesis and paleoenvironmental changes in the Brazilian cerrado. J. Geochem. Explor. 88, 172–176.
Bremond, L., Alexandre, A., Hély, C., Guiot, J., 2005. A phytolith index as a proxy of tree cover density in tropical areas: calibration with leaf Area index along a forest–savanna transect in southeastern Cameroon. Glob. Planet. Change 45, 277–293.
Bush, M.B., Correa-Metrio, A., McMichael, C., Sully, S., Shadik, C.R., Valencia, B.G., Guilderson, T., Steinitz-Kannan, M., Overpeck, J.T., 2016. A 6900-year history of landscape modification by humans in lowland Amazonia. Quat. Sci. Rev. 141, 52–64.
Caffrey, M.A., Horn, S.P., 2015. Long-term fire trends in Hispaniola and Puerto Rico from sedimentary charcoal: a comparison of three records. Prof. Geogr. 67, 229–241.
Caffrey, M.A., Horn, S.P., Orvis, K.H., Haberyan, K.A., 2015. Holocene environmental change at Laguna Saladilla, coastal north Hispaniola. Palaeogeogr. Palaeoclimatol. Palaeoecol. 436, 9–22.
Cassá, R., 1989. Historia social y económica de la República Dominicana. Editorial Alfa y Omega, Santo Domingo, Dominican Republic.
Chandler-Ezell, K., Pearsall, D.M., Zeidler, J.A., 2006. Root and tuber phytoliths and starch grains document manioc (*Manihot esculenta*), arrowroot (*Maranta arundinacea*), and llerén (*Calathea* sp.) at the Real Alto site, Ecuador. Econ. Bot. 60 (2), 103–120.
Chanlatte Baik, L.A., 2003. Agricultural societies in The Caribbean: The Greater Antilles and The Bahamas. In: Sued Badillo, J. (Ed.), Autochtonous Societies, vol. 1. UNESCO, France, pp. 228–246.
Chen, S.T., Smith, S.Y., 2013. Phytolith variability in Zingiberales: a tool for the reconstruction of past tropical vegetation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 370, 1–12.
Clark, G.M., Horn, S.P., Orvis, K.H., 2002. High-elevation savanna landscapes in the Cordillera Central, Dominican Republic, Hispaniola. Mt. Res. Dev. 22, 288–295.
Crosby, A.W., 1972. The Columbian Exchange: Biological and Cultural Consequences of 1492. Greenwood Publishing Group, Westport, Conn., USA.
Crosby, A.W., 2004. Ecological Imperialism; The Biological Expansion of Europe, 900–1900, 2nd ed. Cambridge University Press, Cambridge, UK.
de Las Casas, B., 1875 [1552-1561]. Historia de las Indias. Tomo I. Imprenta de Miguel Ginesta, Madrid, Spain.
de Oviedo y Valdés, G.F., 1851 [1535]. Historia General y Natural de las Indias, islas y tierra-firme del Mar Océano. Imprenta de la Real Aca demia de la Historia, Madrid, Spain.
Deagan, K.A., Cruxent, J.M., 2002. Archaeology at La Isabela: America's First European Town. Yale University Press, New Haven, USA.
Dean Jr., W.E., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. J. Sediment. Res. 44 (1), 242–248.
Dearing, J., Acma, B., Bub, S., Chambers, F.M., Chen, X., Cooper, J., Crook, D., Dong, X., Dotterweich, M., Edwards, M., Thomas Foster, H., Gaillard, M.-J., Galop, D., Gell, P., Gil, A., Jeffers, E., Jones, R., Anupama, K., Langdon, P.G., Marchant, R., Mazier, F., McLean, C., Nunes, L., Raman, S., Suryaprakash, I., Umer, M., Yang, X., Wang, R., Zhang, K., 2015. Social-ecological systems in the anthropocene: the need for integrating social and biophysical records at regional scales. Anthropocene Rev. 2, 1–27. doi:http://dx.doi.org/10.1177/2053019615579128.
Deive, C.E., 2002. Antología de la flora y fauna de Santo Domingo en cronistas y viajeros: siglos XV–XX. Sociedad Dominicana de Bibliófilos, Santo Domingo, Dominical Republic.
Del Río Moreno, J., 2012. Ganadería, plantaciones y comercio azucarero antillano. Siglos XVI y XVII. Academia Dominicana de la Historia, Santo Domingo, Dominican Republic.
Delle, J.A., 2014. The Colonial Caribbean: landscapes of power. Jamaica's Plantation System. Cambridge University Press, Cambridge, UK.
Desjardins, A.A., 2007. Paleoenvironmental Reconstruction of a Coastal Lagoon in Southwestern Dominican Republic. Unpublished master thesis. University of Tennessee, Knoxville.
Dobyns, H.F., 1983. Their Number Become Thinned: Native American Population Dynamics in Eastern North America. University of Tennessee Press, Knoxville, USA.
Ejarque, A., Anderson, R.S., Simms, A.R., Gentry, B.J., 2015. Prehistoric fires and the shaping of colonial transported landscapes in southern California: a paleoenvironmental study at Dune Pond, Santa Barbara County. Quat. Sci. Rev. 112, 181–196.
Fernández de Oviedo, G., 1851. Historia General y Natural de Las Indias TI. Imprenta de la Real Academia de la Historia, Madrid.
Finsinger, W., Tinner, W., 2005. Minimum count sums for charcoal concentration estimates in pollen slides: accuracy and potential errors. Holocene 15, 293–297.
Fitzpatrick, S.M., Keegan, W.F., 2007. Human impacts and adaptations in the Caribbean Islands: an historical ecology approach. Earth Environ. Sci. Trans. R. Soc. Edinb. 98, 29–45.
Foster, D., Swanson, F., Aber, J., Burke, I., Brokaw, N., Tilman, D., Knapp, A., 2003. The importance of land-use legacies to ecology and conservation. BioScience 53, 77–88.
Gebelein, J., 2011. A Geographic Perspective of Cuban Landscapes. Springer, Dordrecht, Heidelberg.
Gelorini, V., Verbeken, A., van Geel, B., Cocquyt, C., Verschuren, D., 2011. Modern non-pollen palynomorphs from East African lake sediments. Rev. Palaeobot. Palynol. 164 (3–4), 143–173.
Gosling, W.D., De Kruif, J., Norder, S.J., De Boer, E.J., Hooghiemstra, H., Rijsdijk, K.F., McMichael, C., 2017. Mauritius on fire. Biotropica 49 (6), 778–783.
Grimm, E., 1993. TILIA: A Pollen Program for Analysis and Display. Retrieved from. Illinois State Museum, Springfield.
Guerrero, J.G., Veloz Maggiolo, M., 1988. Los inicios de la colonización en América: la arqueología como historia, vol. 67. Universidad Central del Este, San Pedro de Macoris, República Dominicana.
Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., Röhl, U., 2001. Southward migration of the intertropical convergence zone through the Holocene. Science 293 (5533), 1304–1308.
Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. J. Paleolimnol. 25 (1), 101–110.
Higuera-Gundy, A., Brenner, M., Hodell, D.A., Curtis, J.H., Leyden, B.W., Binford, M. W., 1999. A 10,300 14 C yr record of climate and vegetation change from Haiti. Quat. Res. 52, 159–170.
Hodell, D.A., Brenner, M., Curtis, J.H., Guilderson, T., 2001. Solar forcing of drought frequency in the Maya lowlands. Science 292 (5520), 1367–1370.
Hodell, D.A., Brenner, M., Curtis, J.H., Medina-Gonzalez, R., Can, E.I.C., Albornaz-Pat, A., Guilderson, T.P., 2005. Climate change on the Yucatan Peninsula during the little ice age. Quat. Res. 63 (2), 109–121.
Hofman, C.L., Hoogland, M.L.P., 2011. Unravelling the multi-scale networks of mobility and exchange in the pre-colonial circum-Caribbean. In: Hofman, C.L., Duijvenbode, A.V. (Eds.), Communities in Contact: Essays in Archaeology, Ethnohistory and Ethnography of the Amerindian Circum-Caribbean. Sidestone Press, Leiden, The Netherlands, pp. 14–44.
Hofman, C.L., Hoogland, M.L.P., 2015. Investigaciones arqueológicas en los sitios El Flaco (Loma de Guayacanes) y La Luperona (Unijica). Informe preliminar. Boletin del Museo del Hombre Dominicano 46 (42), 61–74.
Hofman, C.L., Bright, A.J., Boomert, A., Knippenberg, S., 2007. Island rhythms: the web of social relationships and interaction networks in the Lesser Antillean archipelago between 400 BC and AD 1492. Lat. Am. Antiq. 18, 243–268.
Hofman, C.L., Mol, A.A.A., Hoogland, M.L.P., Valcárcel Rojas, R., 2014. Stage of Encounters: Migration, Mobility and Interaction in the Pre-Colonial and Early Colonial Caribbean. World Archaeology 46, 590–609.
Hofman, C.L., Ulloa Hung, J., Herrera Malatesta, E., Jean, J.S., Hoogland, M.L.P., 2018. Indigenous Caribbean Perspectives. Archaeologies and Legacies of the First Colonized Region in the New World. Antiquity.
Hooghiemstra, H., 1984. Vegetational and Climatic History of the High Plain of Bogotá, Colombia. Dissertationes Botanicae 79. J. Cramer Verlag, Vaduz.
Horn, S.P., Orvis, K.H., Kennedy, L.M., Clark, G.M., 2000. Prehistoric fires in the highlands of the Dominican Republic: evidence from charcoal in soils and sediments. Caribb. J. Earth Sci. 36, 10–18.
Horn, S.P., Kennedy, L.M., Orvis, K.H., 2001. Vegetation recovery following a high elevation fire in the Dominican Republic. Biotropica 33, 701–708.
Iriarte, J., Glaser, B., Watling, J., Wainwright, A., Birk, J.J., Renard, D., Rostain, S., McKey, D., 2010. Late Holocene neotropical agricultural landscapes: phytolith and stable carbon isotope analysis of raised fields from French Guianan coastal savannahs. J. Archaeol. Sci. 37, 2984–2994.
Iriarte, J., Power, M.J., Rostain, S., Mayle, F.E., Jones, H., Watling, J., Whitney, B.S., McKey, D.B., 2012. Fire-free land use in pre-1492 Amazonian savannas. Proc. Natl. Acad. Sci. U. S. A. 109 (17), 6473–6478.
Keegan, W.F., 2013. The 'Classic' Taíno. In: Keegan, W.F., Hofman, C.L., Rodríguez Ramos, R. (Eds.), The Oxford Handbook of Caribbean Archaeology. Oxford University Press, New York, USA.
Keegan, W.F., Hofman, C.L., 2017. The Caribbean Before Columbus. Oxford University Press, New York.
Kennedy, L.M., Horn, S.P., Orvis, K.H., 2005. Modern pollen spectra from the highlands of the Cordillera Central, Dominican Republic. Rev. Palaeobot. Palynol. 137, 51–68.
Kennedy, L.M., Horn, S.P., Orvis, K.H., 2006. A 4000-year record of fire and forest history from Valle de Bao, Cordillera Central, Dominican Republic. Palaeogeogr. Palaeoclimatol. Palaeoecol. 231, 279–290.
Kirch, P.V., 1982. Transported landscapes. Nat. Hist. 91, 32–35.
Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K., Sugi, M., 2010. Tropical cyclones and climate change. Nat. Geosci. 3 (3), 157.
Konert, M., Vandenberghe, J., 1997. Comparison of laser grain size analysis with pipette and sieve analysis: a solution for the underestimation of the clay fraction. Sedimentology 44, 523–535.
Lane, C.S., Horn, S.P., Mora, C.I., Orvis, K.H., 2009. Late-Holocene paleoenvironmental change at mid-elevation on the Caribbean slope of the Cordillera Central, Dominican Republic: a multi-site, multi-proxy analysis. Quat. Sci. Rev. 28, 2239–2260.
Lane, C.S., Horn, S.P., Orvis, K.H., 2008. The earliest evidence of Ostionoid maize agriculture from the interior of Hispaniola. Caribb. J. Sci. 44, 43–52.
LeBlanc, A.R., 2011. A 1000-Year Sedimentary Record of Hurricane, Fire, and Vegetation History from a Coastal Lagoon in Southwestern Dominican Republic. PhD thesis. University of Virginia Tech., USA.
McCook, S., 2011. The neo-Columbian exchange: the second conquest of the Greater Caribbean, 1720–1930. Lat. Am. Res. Rev. 46, 11–31.
McVay, J.L., 2013. A 4700-Year Record of Lake Evolution and Fire History for Laguna Limón, Dominican Republic. PhD thesis. University of Virginia Tech., USA.
Medeanic, S., Dillenburg, S.R., 2005. Palynology and ^{21}Pb datings: first integrated approach to estimating anthropogenic impact on the environment of the

Tramandaí Lagoon and adjacent areas during the last century. J. Coast. Res. Special Issue 42, 271–276.
Mickleburgh, H.L., Pagán-Jiménez, J., 2012. New insights into the consumption of maize and other food plants in the pre-Columbian Caribbean from starch grains trapped in human dental calculus. J. Archaeol. Sci. 39, 2468–2478.
Ministerio de Medio Ambiente y Recursos Naturales [MMARN], 2012. Atlas de Biodiversidad y Recursos Naturales de la República Dominicana. Ministerio de Medio Ambiente y Recursos Naturales, Santo Domingo.
Montoya, E., Rull, V., van Geel, B., 2010. Non-pollen palynomorphs from surface sediments along an altitudinal transect of the Venezuelan Andes. Palaeogeogr. Palaeoclimatol. Palaeoecol. 297, 169–183.
Morcote-Ríos, G., Bernal, R., Raz, L., 2016. Phytoliths as a tool for archaeobotanical, palaeobotanical and palaeoecological studies in Amazonian palms. Bot. J. Linn. Soc. 182, 348–360.
Moscol-Olivera, M., Duivenvoorden, J.F., Hooghiemstra, H., 2009. Pollen rain and pollen representation across a forest-páramo ecotone in northern Ecuador. Rev. Palaeobot. Palynol. 157, 285–300.
Nogué, S., de Nascimento, L., Froyd, C.A., Wilmshurst, J.M., De Boer, E.J., Coffey, E.E.D., Whittaker, R.J., Fernández-Palacios, J.-M., Willis, K.J., 2017. Island biodiversity conservation needs palaeoecology. Nat. Ecol. Evol. 1, 1–9.
Nyberg, J., Malmgren, B.A., Kuijpers, A., Winter, A., 2002. A centennial-scale variability of tropical North Atlantic surface hydrography during the late Holocene. Palaeogeogr. Palaeoclimatol. Palaeoecol. 183 (1–2), 25–41.
Pearsall, D.M., 2000. Paleoethnobotany: A Handbook of Procedures. Academic Press, San Diego, USA.
Pesoutova, J., Hofman, C.L., 2016. La contribución indígena a la biografía del paisaje cultural de la República Dominicana. Una revisión preliminar. In: Ulloa Hung, J., Valcárcel Rojas, R. (Eds.), Indígenas e indios en el Caribe presencia, legado y estudio. INTEC, Santo Domingo, Dominican Republic.
Piperno, D.R., 2006. Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists. Lanham, Rowman Altamira, New York, USA.
Piperno, D.R., Pearsall, D.M., 1998. The Silica Bodies of Tropical American Grasses: Morphology, Taxonomy, and Implications for Grass Systematics and Fossil Phytolith Identification. Smithsonian Institution Press, Washington D. C., USA.
Piperno, D.R., Moreno, J.E., Iriarte, J., Holst, I., Lachniet, M., Jones, J.G., Ranere, A.J., Castanzo, R., 2007. Late Pleistocene and Holocene environmental history of the Iguala Valley, central Balsas watershed of Mexico. Proc. Natl. Acad. Sci. U. S. A. 104 (29), 11874–11881.
Pons, F.M., 1971. La Española en el siglo XVI, 1493-1520: trabajo, sociedad y política en el economía del oro, vol. 10. Universidad Católica Madre y Maestra, Santo Domingo, Dominican Republic.
Prins, M.A., Weltje, G.J., 1999. End-member modeling of siliciclastic grain-size distributions: the late quaternary record of aeolian and fluvial sediment supply to the Arabian Sea and its paleoclimatic significance. In: Harbaugh, J. (Ed.), Numerical Experiments in Stratigraphy: Recent Advances in Stratigraphic and Sedimentologic Computer Simulations. SEPM (Society for Sedimentary Geology) Special Publication 62, pp. 91–111.
Rivera-Collazo, I., Winter, A., Scholz, D., Mangini, A., Miller, T., Kushnir, Y., Black, D., 2015. Human adaptation strategies to abrupt climate change in Puerto Rico ca. 3.5 ka. Holocene 25 (4), 627–640.
Rodríguez Ramos, R., Pagán-Jiménez, J., 2006. Interacciones multivectoriales en el Circum-Caribe precolonial: Un vistazo desde las Antillas. Caribb. Stud. 99–139.
Roubik, D.W., Moreno, P., 1991. Pollen and Spores of Barro Colorado Island. Monographs in Systemaic Botany 36. Missouri Botanical Garden, St. Louis, Miss., USA.
Rouse, I.B., 1992. The Tainos: Rise and Decline of the People Who Greeted Columbus. Yale University Press, New Haven, USA.
Santiago Brilhante, E., Braga, J.M.A., Vieira, R.C., 2013. Morphological characterisation of silica phytoliths in Neotropical Marantaceae leaves. Plant Syst. Evol. 299 (9), 1659–1670.
Schlütz, F., Shumilovskikh, L.S., 2013. On the relation of *Potamomyces armatisporus* to the fossil form-type *Mediaverrunites* and its taxonomical and ecological implications. Fungal Ecol. 6, 309–315.
Schlütz, F., Shumilovskikh, L.S., 2017. Non-pollen palynomorphs notes: 1. Type HdV-368 (*Podospora*-type), descriptions of associated species, and the first key to related spore types. Rev. Palaeobot. Palynol. 239, 47–54.
Schneider, C.A., Rasband, W.S., Eliceiri, K.W., 2012. NIH Image to ImageJ: 25 years of Image analysis. Nat. Methods 9 (7), 671–675.
Siegel, P.E., Jones, J.G., Pearsall, D.M., Dunning, N.P., Farrell, P., Duncan, N.A., Curtis, J. H., Singh, S.K., 2015. Paleoenvironmental evidence for first human colonization of the eastern Caribbean. Quat. Sci. Rev. 129 (1), 275–295.
Siegel, P.E., Jones, J.G., Pearsall, D.M., Wagner, D.P., 2005. Environmental and cultural correlates in the West Indies a view from Puerto Rico. In: Siegel, P.E. (Ed.), Ancient Borinquen. Archaeology and Ethnohistory of Native Puerto Rico. University of Alabama Press, Tuscaloosa, USA, pp. 88–121.
Sonnemann, T.F., Ulloa Hung, J., Hofman, C.L., 2016. Mapping indigenous settlement topography in the Caribbean using drones. Remote Sens. 8 (10), 791.
Steadman, D.W., Martin, P.S., MacPhee, R.D., Jull, A.T., McDonald, H.G., Woods, C.A., Iturralde-Vinent, M., Hodgins, G.W., 2005. Asynchronous extinction of late quaternary sloths on continents and islands. Proc. Natl. Acad. Sci. U. S. A. 102, 11763–11768.
Sued Badillo, J., 1995. The island Caribs. New approaches to the questions of ethnicity in the early colonial Caribbean. In: Whitehead, N.L. (Ed.), Wolves from the Sea. KITLV Press, Leiden, The Netherlands, pp. 61–89.
Tanodi, A., 1971. Documentos de la Real Hacienda de Puerto Rico Volumen I 1510–1519, 1st ed. Editorial NOVA S.A.C.I., Buenos Aires, Argentina.
Toonen, W.H., Kleinhans, M.G., Cohen, K.M., 2012. Sedimentary architecture of abandoned channel fills. Earth Surf. Process. Landforms 37 (4), 459–472.
Tryon, R.M., Tryon, A.F., 1982. Ferns and Allied Plants: With Special Reference to Tropical America. Springer, New York, USA.
Ulloa Hung, J., 2014. Arqueología en la Línea Noroeste de La Española. Paisajes, cerámicas e interacciones. Instituto Tecnológico de Santo Domingo, República Dominicana.
Ulloa Hung, J., Herrera Malatesta, E., 2015. Investigaciones arqueologicas en el norte de la Española. Entre viejos esquemas y nuevos datos. Boletin del Museo del Hombre Dominicano 42, 75–107.
UNEP (United Nations Environment Programme), 2013. United Nations Environment Programme, Haiti—Dominican Republic Environmental Challenges in the Border Zone. United Nations Environment Programme, Nairobi, Kenya.
Valcárcel Rojas, R., 2012. Interacción colonial en un pueblo de indios encomendados: El Chorro de Maíta, Cuba. PhD Thesis. University of Leiden, The Netherlands.
Van Geel, B., 2002. Non-pollen palynomorphs. In: Birks, J.B.H., Lotter, A.F., Juggins, S., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments, vol. 3. Kluwer, Dordrecht, The Netherlands, pp. 99–119.
Van Geel, B., Buurman, J., Brinkkemper, O., Schelvis, J., Aptroot, A., van Reenen, G., Hakbijl, T., 2003. Environmental reconstruction of a Roman period settlement site in Uitgeest (The Netherlands), with special reference to coprophilous fungi. J. Archaeol. Sci. 30, 873–883.
Van Geel, B., Engels, S., Martin-Puertas, C., Brauer, A., 2013. Ascospores of the parasitic fungus *Kretzschmaria deusta* as rainstorm indicators during a late Holocene beech-forest phase around lake Meerfelder Maar, Germany. J. Paleolimnol. 50, 33–40.
Van Geel, B., Gelorini, V., Lyaruu, A., Aptroot, A., Rucina, S., Marchant, R., Sinninghe Damsté, J.S., Verschuren, D., 2011. Diversity and ecology of tropical African fungal spores from a 25,000-year palaeoenvironmental record in southeastern Kenya. Rev. Palaeobot. Palynol. 164 (3), 174–190.
Veloz Maggiolo, M., 1980. Las sociedades arcaicas de Santo Domingo. Museo del Hombre Dominicano and Fundación García Arévalo, Santo Domingo, Dominican Republic.
Veloz Maggiolo, M., 2003. La isla de Santo Domingo antes de Colón. Banco Central de la República Dominicana, Santo Domingo, Dominican Republic.
Wade, P.M., 1990. The colonisation of disturbed freshwater habitats by characeae. Folia Geobotanica et Phytotaxonomica 25 (3), 275–278.
Watling, J., Iriarte, J., 2013. Phytoliths from the coastal savannas of French Guiana. Quat. Int. 287, 162–180.
Watts, D., 1987. Patterns of Development, Culture and Environmental Change Since 1492. Cambridge University Press, Cambridge, UK.
Watts, D., 1999. The Caribbean environment and early settlement. In: Emmer, P.C. (Ed.), General History of the Caribbean, vol. 2. UNESCO, France, pp. 29–42.
Wilson, S.M., 1990. Hispaniola: Caribbean Chiefdoms in the Age of Columbus. University of Alabama Press, Tuscaloosa, USA.
Zurro, D., García-Granero, J.J., Lancelotti, C., Madella, M., 2016. Directions in current and future phytolith research. J. Archaeol. Sci. 68, 112–117.